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The semiconductor manufacturing industry faces the need for tighter control of thermal budget and process variations as circuit feature sizes decrease. Strategies to meet this need include supervisory control, run-to-run control, and real-time feedback control. Typically, the level of control chosen depends upon the actuation and sensing available. Rapid Thermal (RTP) is one step of the manufacturing cycle requiring precise temperature control and hence real-time feedback control. At the outset of this research, the primary ingredient lacking from in-situ RTP temperature control was suitable sensor. This research looks at an alternative to the traditional approach of pyrometry, which is limited by the unknown and possibly time-varying wafer emissivity. the technique is based upon the temperature dependence of the propagation time of an acoustic wave in the wafer. The aim of this thesis is to demonstrate that ultrasonic sensors are a viable sensor for control in RTP. To do this, an experimental implementation was developed at the Center for Integrated Systems. Because of the difficulty in applying a known temperature standard in an RTP environment, calibration to absolute temperature is nontrivial. Given reference propagation delays, multivariable model-based feedback control is applied to the system. The modelling and implementation details are described. The control techniques have been applied to a number of research processes including rapid thermal annealing and rapid thermal crystallization of thin silicon films on quartz/glass substrates.

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Final Technical Report

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Abstract

The semiconductor manufacturing industry faces the need for tighter control of thermal budget and process variations as circuit feature sizes decrease. Strategies to meet this need include supervisory control, run-to-run control, and real-time feedback control. Typically, the level of control chosen depends upon the actuation and sensing available.

Rapid Thermal Processing (RTP) is one step of the manufacturing cycle requiring precise temperature control and hence real-time feedback control. At the outset of this research, the primary ingredient lacking from in-situ RTP temperature control was a suitable sensor. This research looks at an alternative to the traditional approach of pyrometry, which is limited by the unknown and possibly time-varying wafer emissivity. The technique is based upon the temperature dependence of the propagation time of an acoustic wave in the wafer.

The aim of this thesis is to demonstrate that ultrasonic sensors are a viable sensor for control in RTP. To do this, an experimental implementation was developed at the Center for Integrated Systems. Because of the difficulty in applying a known temperature standard in an RTP environment, calibration to absolute temperature is nontrivial. Given reference propagation delays, multivariable model-based feedback control is applied to the system. The modelling and implementation details are described. The control techniques have been applied to a number of research processes including rapid thermal annealing and rapid thermal crystallization of thin silicon films on quartz/glass substrates.

This final report is an executive summary for the thesis work on semiconductor manufacturing [2]. Although phase shifting mask design was included in the title for this proposal, the research focused on an experimental system at the Center for Integrated Systems at Stanford. The following sections outline the chapters in the thesis.

1 Introduction

Chapter 1 summarizes the challenge of Rapid Thermal Processing. The chapter is essentially divided into two sections. The first section describes Stanford's RTP perspective emphasizing the key research ideas. The second section details the control and sensing RTP literature.

For experimental work, this division seems natural because it can be difficult, if not impossible, to inexpensively replicate the work done elsewhere. One distinguishing aspect of the work done at Stanford is the use of an ultrasonic sensor for temperature measurement. This thesis will show that the ultrasonic sensors are a viable sensor for control in Rapid Thermal Processing. It is believed that the further performance enhancements are possible when a system is designed for use with the ultrasonic sensors rather than retrofitting them to an existing system. A diagram of Stanford's RTP system is given in Figure 1.
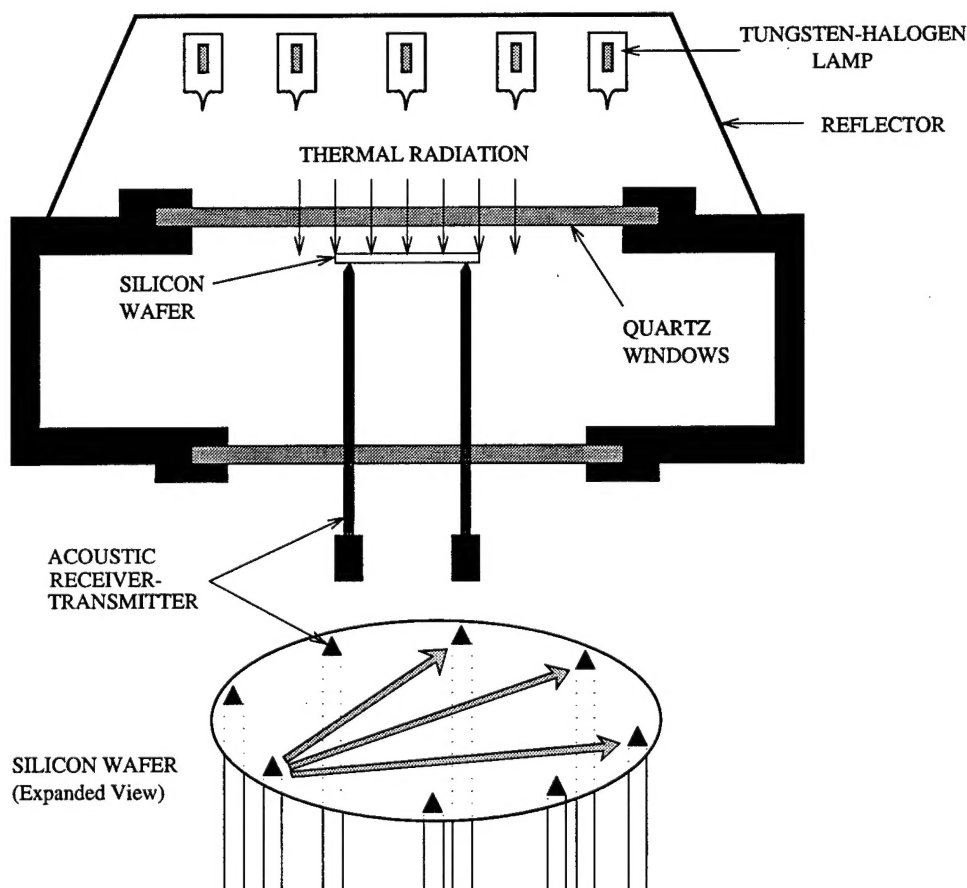
Figure 1: A typical cross-section of a Rapid Thermal Processor using an acoustic thermometry system.

2 Traditional Temperature Measurement

Numerous papers cite the need for accurate temperature measurement in RTP. One challenge is the lack of a standard against which to compare sensors.

To understand this problem, embedded thermocouple wafers are studied. The main purpose of this investigation is to propose a model for localized heat transfer in thin plates. The model shows how local heat losses affect the temperature distribution in a silicon wafer.

Experimental data shows the following results. The thermocouple wires and their placement significantly influence the thermocouple readings. Large deviations (approx. 50 °C) occur depending on the orientation of the thermocouple wires with respect to the lamps at high temperatures (approx. 1000 °C). Incidentally, a negligible change in the oxide growth is observed when the orientation relative to the lamps is changed and the same lamp recipes are run [3]. This work has influenced the junction design of our industrial partner SensArray Corporation. The conclusion from these experiments is to clearly distinguish between *thermocouple reading* and *wafer temperature.*

3 Acoustic Background

This chapter provides the necessary background for acoustics in solids used in this thesis. The acoustic sensing technique was developed under the guidance of B.T. Khuri-Yakub. Yong Jin Lee's thesis *Temperature Measurement in Rapid Thermal Processing Using Acoustic Techniques* [10] introduced the sensing technique and Levent Degertekin [6] extended and refined the acoustic sensor for a manufacturing environment.

This chapter is intended for readers unfamiliar with acoustical theory, it is hoped that this will provide an ascertainable summary in a succinct fashion. The style is predominantly tutorial and for simplicity only non-piezoelectric media (*e.g.* silicon) are considered. This chapter is decoupled from the following chapter for pedagogical reasons – understanding of the underlying physics may be useful in other applications apart from this particular application in RTP. For example, the model of Lamb wave propagation is applied to a parameter estimation problem in Chapter 6.

4 An Acoustic Sensor for RTP

This chapter describes the implementation of the acoustic sensor used in the experimental portion of this thesis [7]. Excitement about these ultrasonic sensors stems from the following:

- A noninvasive in-situ estimate of temperature can be calculated [9, 11].

- Theoretical analysis exists to account for thin film effects of patterned wafers [8].

- In principle, the sensors can operate over a wider temperature regime than pyrometers.

- The dynamics of the ultrasonic sensors are faster than thermocouple sensors [10].

The primary limitations of these sensors include:

- Sufficient mechanical contact between the wafer and the quartz pins is required for coupling the signal into and out of the wafer.

- Wafer placement on the quartz pins is vital to repeatability. Hence, the time of flight to temperature calibration must be done with care.

- The pulse of energy excited in the wafer must dissipate before sending the next pulse. For 100 mm wafers at atmosphere, the maximum pulse rate is around 20 Hz.

This chapter is organized around these strengths and weaknesses. As can be noted above, many of the benefits have been documented elsewhere in the literature. Because the principle aim of this thesis is to develop a feedback controller around this novel sensor, it is important to quantify the sensor's limitations and incorporate this into the design of the control law.

5   Tomography

This chapter looks at tomography in several configurations for a Rapid Thermal Processing system. Ideally, the infinite dimensional (axially symmetric) spatial temperature profile, $T(r)$ for $0 \leq r \leq 1$ could be determined. Because only a limited number of measurements are available, complete profile determination appears prohibitive. Approximations for $T(r)$ can be made, which is the focus of this chapter.

First, the basic Temperature Estimation Problem is defined. To *solve* the problem, we need to express the problem in a framework that is amenable to numerical solution. A variety of different choices exist for setting up and then solving for an approximation to the temperature profile.

The problem is divided into two categories: (1) exact and overdetermined reconstruction and (2) regularized reconstruction. For the first category, a unique least squares error estimate can be obtained under appropriate conditions. The second category, incorporates information about the smoothness of the wafer temperature profile and its derivatives. Using regularized reconstruction allows for the possibility of fewer measurements than unknowns. The problem is formulated as a constrained minimization problem. This can be important when outliers must be removed from the data. Exactly determined reconstruction would require all data associated with that particular measurement set to be eliminated simply because of a single outlier. Typical temperature profiles are generated by an RTP simulator to test various regularization strategies. The results show that this is a reasonable method for estimating the spatial temperature [1].

In addition to this general theory, this chapter describes the design of the three pin sensor plate built in the Center for Integrated Systems at Stanford. The three pin sensor plate designed was optimized in the sense of minimizing the condition number of the matrix which maps time of flight into temperature. The solution to the original formulation as an unconstrained minimization problem places two of the three sensor directly across from one another on the wafer. This configuration is unstable in the sense that the wafer will not be balanced; equivalently one of the contact forces goes to zero. To overcome this difficulty, the problem was reformulated as a constrained minimization problem. The constraint is that the contact force between the wafer and the pin must be greater than some normalized threshold value. Sufficient contact force also assures that Hertzian contact will provide enough energy coupling between the quartz pins and the wafer. Figure 2 shows a tradeoff curve for condition number versus the contact force.
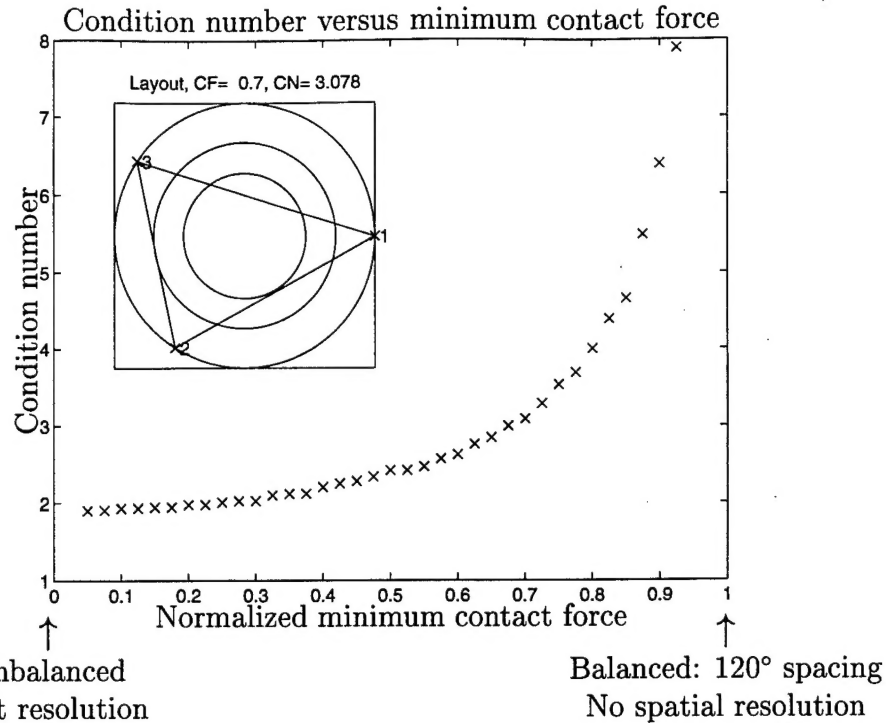
Condition number versus minimum contact force

Layout, CF= 0.7, CN= 3.078

Unbalanced
Best resolution

Balanced: 120° spacing
No spatial resolution

Figure 2: Condition number versus minimum contact force among the three pins.

6   Parameter Identification

Parameter identification is investigated in relation to the received signal. By using the Cramer-Rao lower bound, limits of performance are given on the accuracy of distance and thickness parameter estimates. The drawback to using this information in semiconductor wafers is that the received signal contains multipath information. However, knowledge of such performance figures may be applicable to other acoustic applications where multipath is less of a concern.

7   Process Control with Acoustic Sensor

The RTP system located in the Center for Integrated Systems served as the platform to test these ideas experimentally. The system was developed in conjunction with the Texas Instruments/Microelectronics Manufacturing Science and Technology (TI/MMST) program [12, 5].

Modelling was done using the ESPRIT algorithm and an LQG controller was designed around a particular operating point. The controller takes TOF readings as inputs and changes the lamp powers. The setpoints used by the TOF controller are determined by a calibration procedure involving a thermocouple wafer. TOF steps of 50 °C are shown in Figure 3. The average temperature along both paths is successfully controlled [4].

While most of the control development has occurred on silicon wafers, it is possible to extend these results to other configurations such as quartz wafers. For example, these techniques are applied to the study of crystallization of thin Si/SiGe films on quartz [13].

Crystallization of thin Si/SiGe films for use in thin film transistors (TFTs) using rapid thermal annealing (RTA) offers great promise to the flat panel display industry. Temperature is commonly
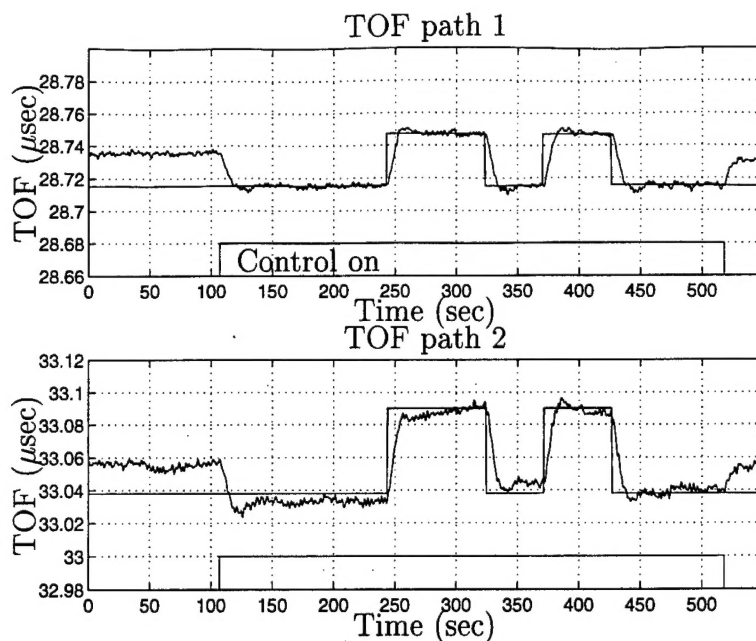
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Figure 3: The TOF steps corresponding to 50 °C steps in temperature. The "Control on" line indicates when the closed-loop control is applied.

measured using pyrometry, which infers temperature from emissivity. Thus, this technique is eminently unsuitable for crystallizing films, which undergo rapid changes in emissivity due to phase changes. Also, no simple means of in-situ monitoring of film crystallinity exists.

The ultrasonic sensors are being used to monitor crystal growth during processing. The time of flight readings are a strong function of temperature but independent of emissivity. Heat absorption by the substrate in an RTA is a function of film emissivity, and hence, of crystallinity. By isolating temperature from emissivity, it is possible to track crystallinity. Our results have established that TOF is suitable for determining crystallization end-points, and is also sensitive enough to identify the onset of crystallization prior to any visible change in film transparency.

This novel tool for determining film crystallinity and temperature simultaneously, providing a means of minimizing thermal budgets and also modelling crystallization processes.

8   Conclusions

Brief Summary of Accomplishments
Recognized limitations of existing technology (pyrometry, thermocouples).
Transferred technology to SensArray, Inc.
Investigated ultrasonic sensing technology.
Designed and debugged system for RTP.
Demonstrated multivariable control in RTP using ultrasonics.
NATO Advanced Study Institute presentation (Acquafredda, Italy)
Application of sensing to Flat Panel Display technology.

This chapter concludes the thesis and suggests directions for future research. I would also like to

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